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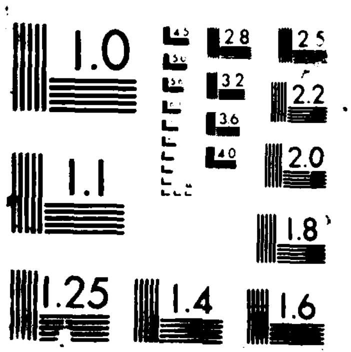
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HOW QUICKLY CAN ATTENTION AFFECT FORM PERCEPTION?

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It is possible to attend to different locations in the visual field without changing fixation. Recently, some researchers have suggested that sequences of such internal attention shifts may be a necessary part of perception. This seems to require that attention be shifted very rapidly, since a complex scene can often be seen with only brief presentation. The present experiments trace the time course of the effects of internal attention shifts on form discrimination accuracy. Observers were cued to attend to one of four peripheral locations while maintaining central fixation. After a brief variable interval, four T-like target figures were presented, one at each location, followed by masks. The observer then identified the target that appeared at the cued location. The first two experiments showed that rapid-onset attention effects, which occur when the cue is presented near the target, can also be obtained with a cue presented at fixation, given sufficient practice. This argues that such effects are indeed attentional in nature and are not due to local cue-target interactions. The third experiment showed that even when the possibility of attention shifts during target presentation is considered, the latency of attention effects is very short. Furthermore, attention increases the rate at which information is extracted from a stimulus.

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SUMMARY

This research examines the phenomenon of <u>internal attention shifting</u>; that is, paying attention to different places in the visual field without changing the direction that the eyes are pointing. Recently, some researchers have suggested that sequences of internal attention shifts may be a necessary part of visual perception. This seems to require that attention be shifted very rapidly, since a complex scene can often be seen with only brief presentation. The purpose of the experiments in this report was to find out how fast such attention shifts are. The results indicated that it is possible to shift attention from one visual location to another in less than 68 milliseconds, but that vision continues to improve for 120-150 milliseconds after a cue to shift attention. Furthermore, it was shown that attention increases the rate at which information is extracted from a stimulus. Thus, internal attention shifts are fast enough to be used in normal visual perception. They may also be a component of skilled performance in vision-dependent tasks.

PREFACE

This basic research was performed in support of 6.1 program objectives of the Air Force Office of Scientific Research Task No. 2313T3, Perceptual and Cognitive Dimensions of Pilot Behavior. Funds for the research were provided by Contract No. F33615-84-C-0066 to the University of Dayton Research Institute from the Operations Training Division of the Air Force Human Resources Laboratory. I thank Drs. Marylou Cheal, George Geri, Julie Lindholm, and Elizabeth Martin for their valuable comments, and Chris Voltz for his assistance in software development.

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I. INTRODUCTION

A variety of experiments have shown that one can attend to different locations in the visual field without changing fixation. Such a change in attended location will be referred to as an "internal attention shift." Internal attention shifts result in increased speed and accuracy of responses to a stimulus presented at or near the new attended location (Bashinski & Bachrach, 1980; Posner, 1980). Both detection and discrimination performance are enhanced (Eriksen & Hoffman, 1972a, 1972b, 1973; Remington, 1980).

Are internal attention shifts a laboratory curiosity, or a necessary part of vision? Treisman and her colleagues (Treisman & Gelade, 1980; Treisman & Paterson, 1984; Treisman & Schmidt, 1982) have argued that attention shifts are used to conjoin visual features into the percept of a unified object at a specific location. Further, Ullman (1984) has suggested that attention shifts are essential for correctly perceiving the extent of visual boundaries and the spatial relationships among them. For example, the process of deciding whether or not two points fall on the same boundary might require that the boundary be "traced" from one point to the other using attention shifts.

These and other ideas about the role of internal attention shifts in constructing the visual percept share at least one common assumption: that changes in the visual location being attended can be made very rapidly. It is, after all, possible to see many of the objects in a visual scene, with their features correctly conjoined, after brief tachistoscopic presentations (e.g., Biederman, 1972). This could require numerous attention shifts during a half-second viewing. Does the focus of attention really change that quickly?

Studies of internal attention shifts have shown that, under some conditions, the effects of a shift can be measured 50 milliseconds after the onset of a cue indicating the location of the target (Colegate, Hoffman, & Eriksen, 1973; Eriksen & Hoffman, 1972b, 1973; Posner, 1980; Posner & Cohen, 1984). Bergen and Julesz (1983), using a paradigm that did not involve location cuing, also inferred an attention shift latency of about 50 milliseconds. In other instances, however, effects did not appear until several hundred milliseconds later (Posner, 1980; Remington, 1980; Remington & Pierce, 1984; Sperling & Reeves, 1980).

In experiments that showed evidence for rapid attention effects, the cue to shift attention was usually a stimulus located near the target. This kind of cue will be referred to as a "target-area cue," to distinguish it from a foveal cue, which is presented at fixation. A typical foveal cue is an arrow that points to the target area. Studies using this cue are among those in which attention effects were slower to develop.

Much of the data relevant to attention-shifting speed has been obtained in the context of a "moving spotlight" view of attention. Shulman, Remington, and McLean (1979) presented evidence that when

attention is shifted from one visual location to another, it moves in an analog fashion over the intervening points in the visual field, like a moving spotlight. Tsal (1983) attempted to infer the speed of this hypothetical analog attention-shifting process using a target-area cue. He arrived at an estimate of 8 milliseconds per degree of visual angle traversed. However Remington and Pierce (1984), using a foveal cue, claimed that the latency of attention effects does not depend on the distance traveled by the shift. Finally, Reeves and Sperling (in press) proposed a model of attention that does not include an analog shift component. In their model, an "attention gate" opens up over time at the to-be-attended location. In the experiments from which this model was derived, the latency of attention shifts to a complex foveal cue was found to be relatively long (200 to 400 milliseconds).

At least two factors complicate attempts to measure the latency of attention effects on form discrimination. One is the aforementioned latency difference between target-area and foveal cues. Jonides (1981) showed that foveal and target-area cues also differ in the degree to which they automatically elicit attention shifts. Target-area cues do not interfere with a concurrent memory task as foveal cues do, and they affect performance even when they are not helpful and subjects are trying to ignore them. All of these results raise the possibility that the rapid target-area cue effect is either mediated by a very specialized attentional mechanism or is not an attentional effect at all. For example, target-area cue effects might be due to lateral masking, or to residual activity in peripheral visual channels. On the other hand, the long latency of foveally cued attention shifts might simply be due to the time required to interpret the cue and determine where to direct attention. The process of actually changing the locus of attention, and its subsequent effects on form discrimination, might be the same for both cue types.

The first two of the present experiments were directed in part toward resolving this issue. The time courses of attention effects resulting from both kinds of cues were measured and compared. The result was that the major differences in time course due to cue type were nearly eliminated by extensive practice with the foveal cue. The remaining difference in the latency of attention effects is probably due to a small difference in the time required to interpret a foveal arrow cue versus a target-area flash.

A second obstacle to determining the temporal characteristics of attention effects on form discrimination is that form discrimination itself takes time. In the task of detecting a luminance increment, the target is typically presented for 5 milliseconds or less, whereas form discrimination usually requires that the target be present for tens of milliseconds. This presents a potential problem. Should one assume that the time available for attention shifting is the time between the onset of the cue and the onset of the target, or the time between the onset of the cue and the offset of the target? Since some of the time that the target is present could also be used for attention shifting, a latency derived from the typical practice of plotting performance as a function of cue-target onset asynchrony could be a serious underestimate.

The second and third experiments examined this issue by measuring the time course of attention effects for varying target durations. The results were compared to predictions based on the assumption that the latency of the first measurable attention effects on form discrimination is relatively long (greater than 100 milliseconds including stimulus presentation time). These predictions were not confirmed; the data show that attention effects begin very quickly at the target location. Furthermore, it appears that attention can increase the rate at which information is extracted from a stimulus. This latter result led to the development of a model of the temporal aspects of internal attention effects.

II. EXPERIMENT 1: TIME COURSE OF ATTENTION EFFECTS FOR FOVEAL VS. TARGET-AREA CUES

In this experiment, the effects of internal attention shifts on the discrimination of T-like target figures were assessed using a paradigm that combines some elements of experiments cited earlier by Posner (1980), Remington (1980), and Bashinski and Bachrach (1980). A cue directed attention to the location of a target figure. The time between cue onset and target onset (i.e., the time available to shift one's attention before the target arrived) was varied. This time will henceforth be called the "cue-target onset asynchrony (CTOA)."

If attention can indeed be moved to the target location during the CTOA, and if it can improve form discrimination accuracy, then the proportion of correct discriminations should increase as more time is allowed to shift attention. Plotting performance as a function of CTOA yields a time course of attention effects.

Of particular interest in Experiment 1 was a comparison of the time courses obtained with foveal cues and target-area cues. Differences in latency obtained with these cue types are theoretically important for two reasons: (a) the aforementioned possibility that the target-area cue effect may not be an attentional effect at all, and (b) the notion that the target-area cue may not be representative of how attention is normally directed. During a single fixation of a real scene, one's attention is seldom driven by a series of abruptly appearing peripheral cues. It is therefore possible that the foveal cue is more characteristic of the way internal attention shifts are normally initiated. One might then conclude from the existing data that foveally cued attention shifts would be too slow to be involved in the kind of object perception operations posited by Treisman, Ullman, and others. However, most of the existing experiments used detection tasks and reaction time measures. No experiment has used form discrimination accuracy to compare the time course of attention effects for the two cue types; so, it was necessary to determine whether a large latency difference exists under these conditions.

Method

Observers. Three observers (two females, one male) with normal vision were tested. None had participated in similar experiments before.

All were paid $7/hour plus a small bonus for correct responses independent of condition.

Apparatus. Stimuli were presented on an Amdek 300-A video monitor controlled by an International Business Machines personal computer (IBM-PC) using a non-interlaced 60 Hz frame rate. The phosphor was P-31, which decays to 10% of initial radiant energy in 40 microseconds. The luminance of the stimuli was 26.4 cd/m^2, and they were displayed on a dark surround. The right eye of each observer was monitored using a standard video camera with zoom lens and a separate display monitor. Adjustable head and chin rests were used to maintain head position 29.7 cm from the stimuli.

Stimuli. Each of four target stimuli consisted of a 1- by 1-degree plus sign with one of its arms removed to yield a T-like figure. The mask followed the outer contours of a plus sign (see Figure 1). The actual stimuli were light-on-dark, though their depiction in the figure is dark-on-light.

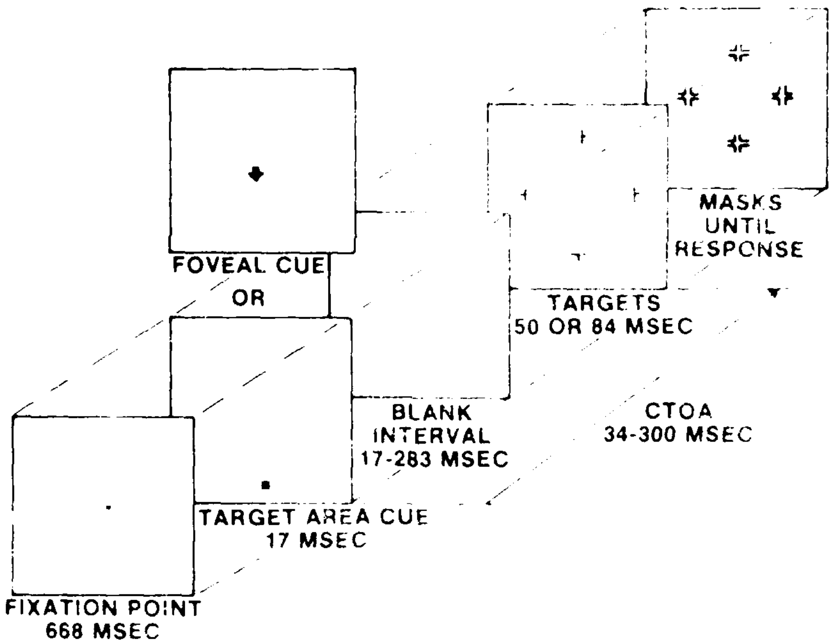

Figure 1. Sequence of Events on Each Trial, Experiment 1.

Procedure. Figure 1 shows the sequence of events for each experimental trial. First, a small fixation dot was presented for 668 milliseconds in the center of the display. The dot then disappeared, and at the same time, a cue appeared to tell the observer which target location would contain the relevant target. In the target-area cue condition, a 0.5-degree square was presented either 4 or 7 degrees to the right, left, above, or below the fixation point. This square was the cue

to the location of the relevant target. In the foveal cue condition, a 0.5-degree arrow was presented at the fixation point. The arrow pointed either left, right, up, or down. Both target-area and foveal cues were displayed for one video frame (17 msec). There followed a blank interval that varied in duration between 17 and 283 msec. The sum of the (constant) cue duration and the blank-interval duration is the CTOA. On each trial, one of 10 CTOAs was randomly selected (34, 50, 67, 84, 117, 134, 167, 200, 267, or 300 msec).

Following the blank interval, four target stimuli were presented, to the right, left, above, and below fixation. All targets were presented either 3 or 6 degrees from the fixation point. The target to be presented at each location on a given trial was randomly selected, with replacement from the set of four T-like figures described above. Stimuli remained illuminated for either 50 or 84 milliseconds and then were masked. The masks remained in place until the observer had decided which stimulus had been presented in the cued location and had indicated his or her decision by depressing one of the four arrow keys on the IBM-PC numeric keyboard. When a response was made, the observer was presented with feedback as to its correctness, and the next trial was initiated.

Observers were instructed to maintain fixation in the center of the display. They were informed when significant eye movements occurred, although stimulus presentation was too rapid to allow a saccade to the target. Thus, eye movements could only diminish performance through saccadic suppression.

The experiment consisted of eight 1-hour sessions. Each session consisted of five blocks of 100 trials each. Within a block, the same target eccentricity, target duration, and type of cue were used. The order of presentation of the resulting eight conditions was counterbalanced.

Pretraining. Prior to their participation in the experiments, all observers were pretrained on foveal identification of the four possible targets. On each pretraining trial, one of the four possible targets was presented foveally for a duration which varied according to the observer's performance on the previous trial. If the previous trial was correct, a counter was decremented. When the decrement totaled 17, the stimulus duration was reduced by one video frame (17 msec). If the preceding trial was incorrect, the counter was incremented. The size of the increment and decrement was controlled so that overall proportion correct would be as close to 0.625 as possible. This proportion represents 50% correct discrimination when corrected for guessing.

Immediately following the presentation of the target, the mask was presented, and the observer decided which target had appeared. Following the observer's response on the computer keyboard, the value of the counter representing stimulus duration was displayed. Observers were told that this number would get smaller if their answer was correct and larger if it was incorrect, and that they should try to obtain as small a number as possible. Observers were pretrained on 1,500 target identification trials before starting the experiments. Previous data indicated that this was sufficient practice for performance to asymptote.

Statistical Analysis. In all ... differences among the proportion ... under different conditions were tested for signi... square tests with alpha = 0.01. Differences ... assessed by: (1) determining differences be... corresponding points, and (2) ... using chi-square statistics, ...

...sults and Discussion

...igure 2 shows the propo... function of CTOA for both fove... discrimination performance inc... available for shifting attenti... significant for both kinds of ... ... .01; foveal: ... - 21.... represent averages over both ta... Target eccentricity, within the ... significantly affect performance ... ... $\chi^2(1)$ = 3.25, p ... ... but only for the ... ... 42.0, p ... .01; foveal ...

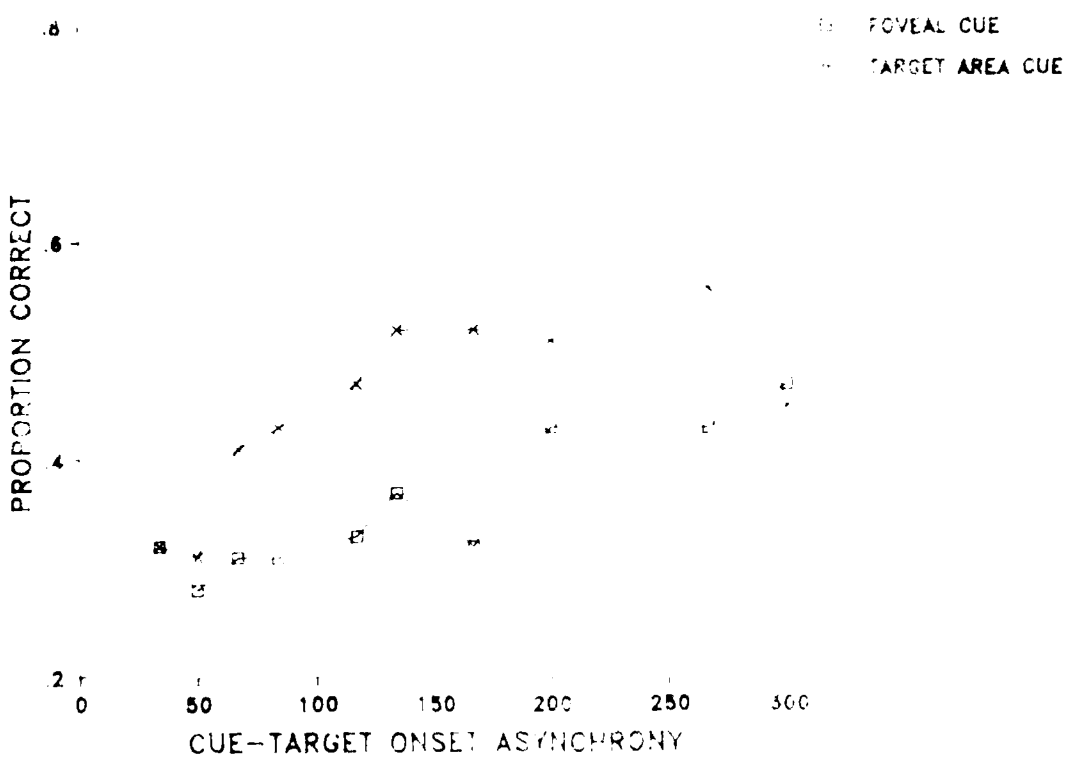

Figure 2. Proportion of Correct Discrimination ... of CTOA for Both Foveal and Target-Area Cues, Experiment 1.

The critical aspect of the data of [illegible] jure 2 is the effect of cue type on performance. For the target-area cu[illegible] effects of attention were present after a CTOA of only 50 millise[illegible]ds, whereas for the foveal cues, effects were much slower to develop. There was no clear effect of increasing CTOA in the foveal cue con[illegible]on before about 150 msec. Consequently, average proportion corr[illegible] was significantly higher for the target-area cues than for the foveal [illegible] (.47 vs. .38, $x^2[1] = 20.8$, $p < .001$). Thus, the results are con[illegible]nt with those obtained for luminance increment detection, in that the latency of attention effects appears to be much greater with the [illegible]t-area cues than with the foveal cues. In addition, the data show th[illegible] or the target-area cues, performance was near asymptote after [illegible]t [illegible]0 milliseconds, whereas for the foveal cues, a clear asymptote [illegible] ot reached within the range of the CTOAs sampled.

It is evident from this exper[illegible] t[illegible] the time courses of attention effects differ for the two types [illegible]es. It is possible that the actual operation of shifting attention [illegible] for both cue types; however, determining where to atte[illegible] tak[illegible] ge[illegible] th the foveal cue. This could occur because the relati[illegible]ip[illegible] n [illegible] foveal cue and the exact visual location to be attended [illegible] b [illegible] ne[illegible] nd thus the to-be-attended location must be retriev[illegible] ro[illegible] ry [illegible] each trial. One way to assess this possibility is to e[illegible]ne [illegible] ti[illegible] urse of attention shifts after large amounts of practic[illegible] it[illegible] fo[illegible] cues. If shifts that are cued foveally are slower only [illegible] au[illegible] ust be interpreted, then automating this process [illegible] u[illegible] t[illegible] should result in much faster foveally cued shifts.

III. EXPERIMENT 2: EFF[illegible] CUE PRACTICE AND TARGET DURATION

This experiment was de[illegible] etermine whether extensive practice markedly alters the time cou[illegible] oveally cued attention shifts, as would be expected under the hyp[illegible]esis that the differences found in Experiment 1 are due to differences in the speed of interpreting the cue. If the latency and magnitude of foveally cued shifts can be brought into the range of those found with the peripheral cue, then it would be clear that fast cuing effects are possible under conditions that rule out lateral masking or other target area interactions.

To the extent that large practice effects occur, their generality becomes an issue. Therefore, practice was given in only two of the four possible directions and one of the two possible eccentricities. Potential effects of practice on identifying the target were minimized by the large number of target identification pretraining trials given prior to Experiment 1.

Method

This experiment was run immediately after Experiment 1, using the same observers, equipment, and procedure. Before the data were collected, observers were given 7,500 practice trials using only the foveal cue. During the practice phase, targets could occur in only two positions

(above or below the fixation point) and at only the 6-degree eccentricity. A target duration of 84 msec was used for the first 4,000 trials. For the final 3,500 trials, the target duration was 50 milliseconds.

During practice, the CTOA was varied on a trial-by-trial basis using the same adaptive procedure that was used for varying stimulus duration during the pretraining phase of Experiment 1. Again, a counter that represented CTOA was decremented after a correct response and incremented after an incorrect response, and observers attempted to minimize the counter value. The initial value of the counter was 200, which represented a CTOA of 234 milliseconds.

Results and Discussion

As in Experiment 1, discrimination performance increased significantly with increasing CTOAs for both foveal and target-area cues (target-area: $x^2[9] = 56.6$, $p < .001$; foveal: $x^2[9] = 27.7$, $p < .005$). However, extensive practice substantially changed the differences found in Experiment 1 between foveal and target-area cues. In fact, practice completely eliminated the effect of cue type on average proportion correct (target-area--.65, foveal--.64, $x^2[1] = .34$, $p > .25$). Figure 3 shows the relationship between CTOA length and performance for both cue types in both experiments. In Experiment 1, the CTOA at which a particular proportion correct was reached was roughly 150 milliseconds longer for foveal cues than for target-area cues. In Experiment 2, this difference was 25 to 50 milliseconds. Some difference between the two conditions would be expected even after practice because use of the foveal cue would still require the retrieval of the to-be-attended location from memory. But there is no longer much reason to suspect that the time courses associated with the two cues reflect totally different phenomena.

As in Experiment 1, there was no significant effect of target eccentricity for either cue type (target-area: $x^2[1] = 2.86$, $p > .05$; foveal: $x^2[1] = 1.68$, $p > .10$). However, the stimulus duration effect was significant for both cue types (target-area: $x^2[1] = 31.8$, $p < .001$; foveal: $x^2[1] = 11.8$, $p < .001$). This finding is discussed further below.

Another issue was the generality of the observed practice effects. The overall proportion of correct responses improved greatly with practice for both cue types (target-area: $x^2[1] = 57.8$, $p < .001$; foveal: $x^2[1] = 123.6$, $p < .001$). There was also significant improvement ($p < .01$) for all target directions, durations, and eccentricities. None of the interactions between these variables and practice was significant. There was, however, a significant interaction between practice and cue type ($x^2[1] = 6.34$, $p < .001$). Because performance improvements with practice were not confined to the particular shift direction, eccentricity, or cue type that was practiced, practice must have improved either the speed of shifting attention itself or, more likely, extraneous aspects of the task. However, the significant interaction between cue type and practice indicates that there was a component of practice effects that was specific to cue type. This result would be expected if one of

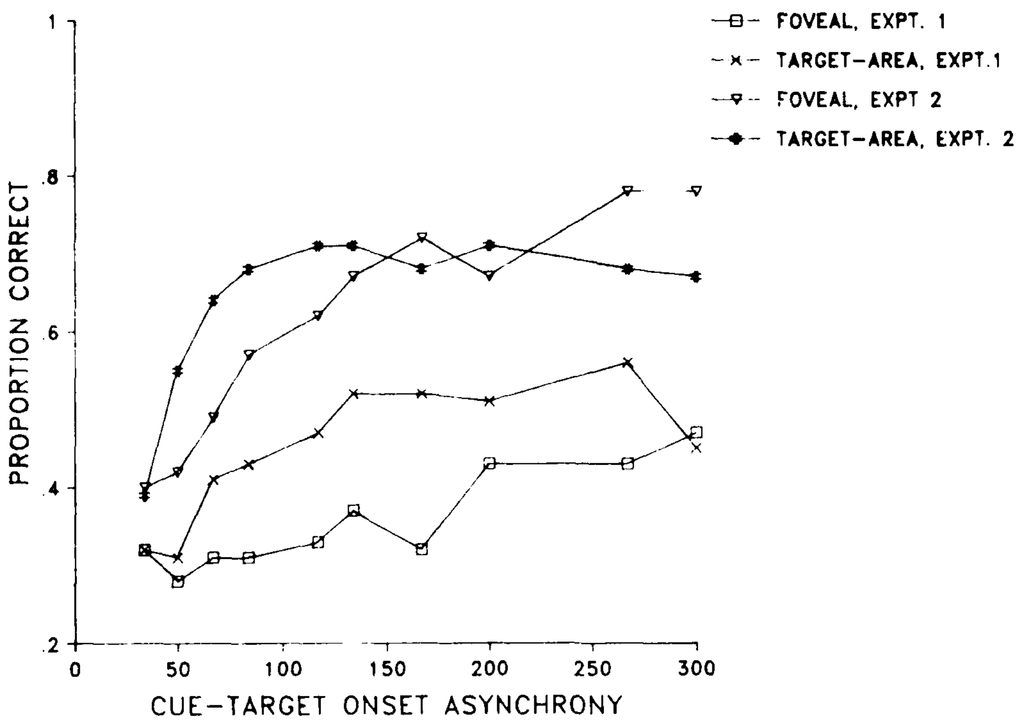

Figure 3. Proportion Correct as a Function of CTOA for Both Foveal and Target-Area Cues, Experiments 1 and 2.

the effects of practice was to strengthen the association between the foveal cue and the to-be-attended location.

Given the main results of this experiment, it seems reasonable to assume that both foveal and target-area cues can initiate a shift of internal attention to a new target location. We now return to the original question that motivated the research: How quickly can such an attention shift begin to affect form discrimination?

Suppose that the data from the target-area cue condition of Experiment 2 reflect the time course of a change in internal attention locus. Based on these data, as shown in Figure 3, it is clear that an improvement in performance occurs between 34 and 50 milliseconds. This could be interpreted to mean that the latency of attention effects is less than 50 milliseconds. Considering that it must take some time to detect and localize the cue, these data might be thought to imply that changing attentional locus is a very rapid process; but there is a problem with such an interpretation.

The problem may be illustrated by considering a model in which attention acts like a "shutter" that does not open until 100 milliseconds after the onset of the cue. Suppose that the duration of the target is 50 milliseconds. If the CTOA is 34 milliseconds, then the total time from

the onset of the cue to the onset of the mask is 84 milliseconds. Thus, the shutter will not have opened when the mask appears, and performance will be at baseline. With a CTOA of 67 milliseconds, however, the CTOA plus target duration is 117 msec; so, the shutter will have been open for 17 milliseconds before the mask appears. A CTOA of 84 milliseconds means that the target would be in view for 34 milliseconds before being masked, and so on. Under these conditions, performance would asymptote at a CTOA of 100 milliseconds, since the shutter would open in time to reveal the target for its entire duration. This is, in fact, approximately the point at which the target-area data for Experiment 2 reached asymptote.

This simple model shows that increases in performance with small CTOAs do not necessarily imply very rapid attention shifts. The shutter model is merely an illustrative device, but the same considerations would hold for a model in which 100 msec or more were required for the focus of attention to shift across visual space, arrive at the target, and thus begin to affect performance. Nothing in the data as analyzed so far rules out this possibility. However, the shutter model implies that varying the duration of the target should markedly affect the observed time course of attention effects. Specifically, as target duration is reduced, longer CTOAs are required before the effects of attention begin to appear.

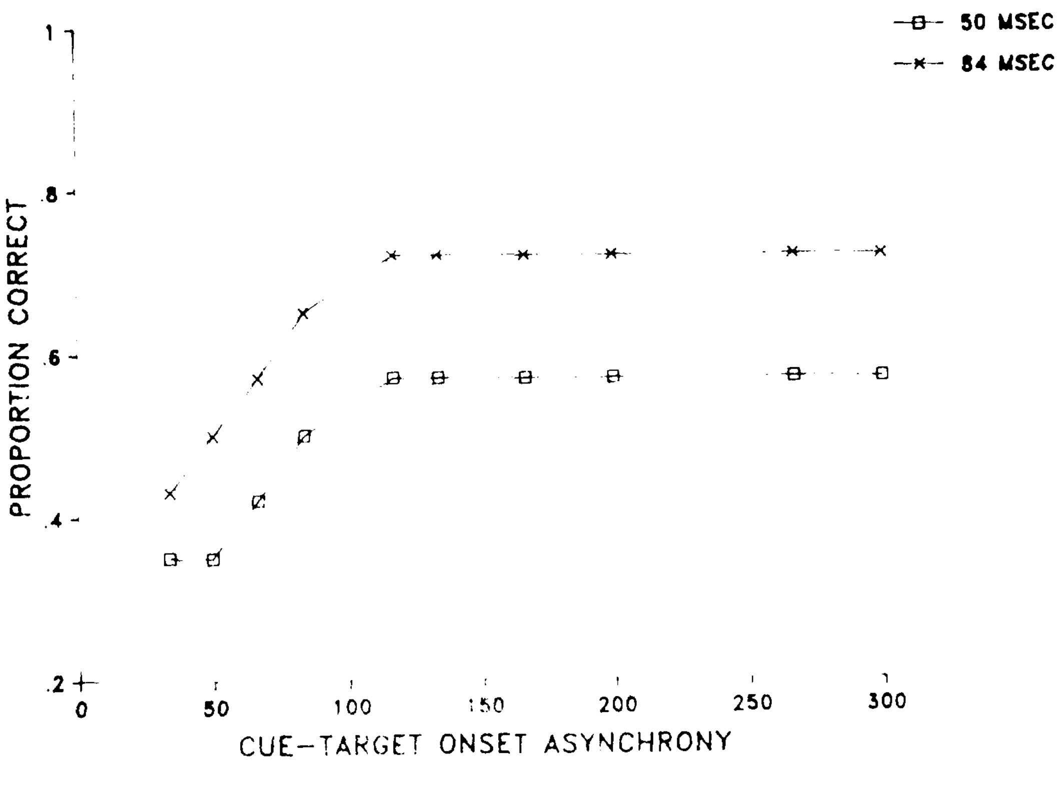

Figure 4. Predicted Effect of Target Duration on the Time Course of Attention Effects, Assuming a Long Attentional Latency (see Equation 1).

Figure 4 shows hypothetical data that illustrate this effect, again assuming that attention operates like a shutter that opens 100 msec after the cue. The two curves in the figure were computed for the two target durations (50 msec and 84 msec) of Experiments 1 and 2, using the equation:

$$\text{Proportion Correct} = ((TD + CTOA) - 100) * .0045 + .35 \qquad (1)$$

where TD denotes target duration, and the quantity ((TD+CTOA)-100) has a *maximum* value of TD and a minimum value of zero. The relative height of each point depends on the length of time that the target remains visible after the hypothetical shutter opens. As the figure shows, varying the duration of the target does not affect the point at which the curve asymptotes, but does affect the point at which it starts to rise. After the curves begin to rise, they are parallel.

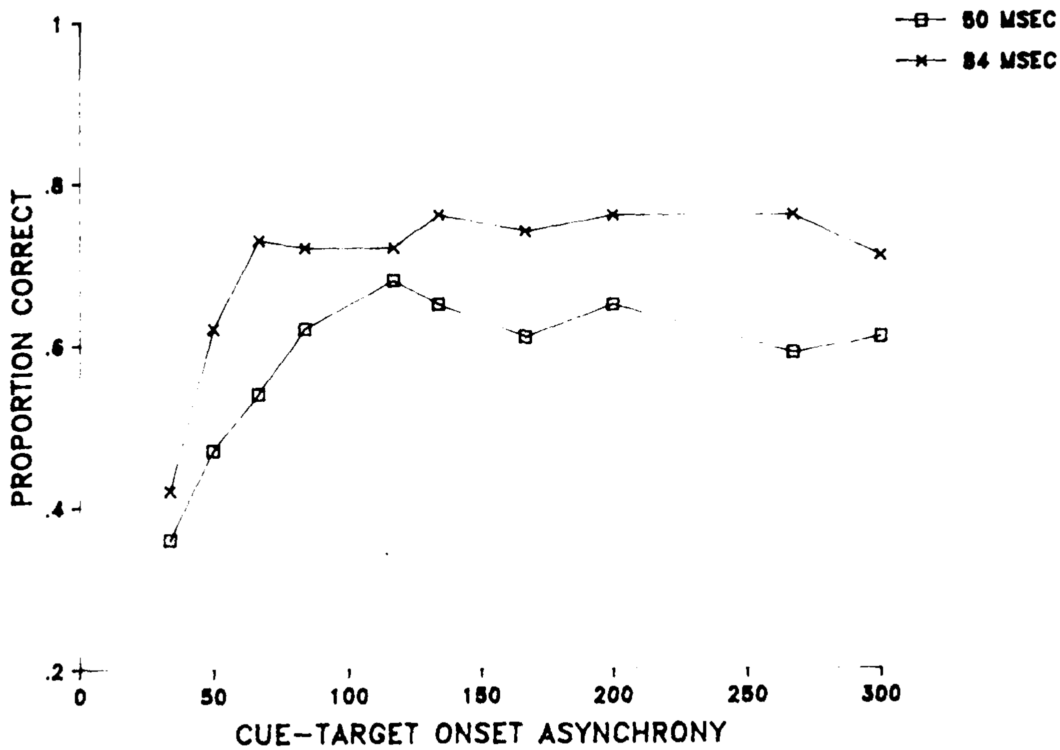

Figure 5. Proportion Correct as a Function of CTOA for 50 and 84 msec Target Durations. Data are from the target-area cue condition of Experiment 2.

Figure 5 shows the target-area cue data from Experiment 2 plotted separately for each of the two target durations. Some aspects of these results *do not* match the hypothetical shutter model predictions of Figure 4. First, the experimental curves both appear to rise at the same point; there is no indication that the 50-msec curve rises later. Second, the curves do not appear to asymptote at the same CTOA; the 84-msec curve appears to asymptote earlier. Third, the 84-msec curve appears to rise more steeply.

To summarize the foregoing analysis: The fact that attention effects appear at short CTOAs does not rule out models in which attention has a long latency, since attention may shift during target presentation. However, when the data for two different target durations were compared, some predictions of a long-latency model (i.e., effects beginning at different CTOAs and reaching asymptote at the same CTOA) were not confirmed. Because these results are critical for making distinctions between long- and short-latency models, it was necessary to attempt to replicate them in a larger experiment.

IV. EXPERIMENT 3: EFFECT OF VARYING TARGET DURATION: A TEST OF LONG-LATENCY MODELS

In order to reconcile long latencies for attention shifts with the observed increase in discrimination performance at small CTOAs, it must be assumed that attention continues to shift to the target location while the target is being presented. Thus, if the target duration is reduced, a correspondingly larger CTOA should be required to produce a rise in discrimination performance. Short-latency models, however, would predict that performance rises at small CTOAs regardless of the target duration.

In this experiment, a 34-msec target-duration condition was investigated, along with the 50-msec and 84-msec conditions used in Experiments 1 and 2. Smaller CTOAs were used, CTOAs were sampled more densely, and the number of experimental trials per observer was increased from 2,000 to 7,000.

Method

Observers. Three female observers with normal or corrected-to-normal vision were each tested for 11 sessions of approximately 1 hour each. None of the observers had participated in Experiments 1 and 2. Two of them, however, had participated in similar experiments. They were paid $7/hour plus a small bonus for correct responses independent of condition. The third observer was a staff member who received no compensation beyond her regular salary.

Apparatus. Stimuli were presented on an IBM Enhanced Color Monitor and controlled by an IBM-PC/XT containing an Enhanced Graphics Adapter. Decay times for the phosphors (P-22-B, P-22-G, and P-22-R) were less than 1 msec. Stimuli were presented on a dark background. Their luminance was 13.7 cd/m^2. As in Experiments 1 and 2, eye position was monitored using a video camera with zoom lens, and a separate display monitor. Adjustable head and chin rests were used to maintain head position.

Stimuli. Stimuli and masks were the same as those used in Experiments 1 and 2; however, the pixel density was increased from 64 to 112 pixels per character.

Procedure. The experimental procedure was the same as in Experiments 1 and 2, with the following exceptions: (a) The fixation point remained illuminated during the entire experimental trial. (b) The experiment used

13 CTOAs (16.7 to 217 msec in 16.7-msec steps), three target durations (34, 50, and 84 msec), one eccentricity (6 degrees), and one cue type (target-area). (c) Seven experimental sessions and one practice session of 1,000 trials each were run. (d) A full-attention target discrimination session was run once prior to the practice and experimental sessions, and twice after their conclusion. The purpose of these sessions was to obtain an estimate of the rate at which target discrimination performance improves with presentation duration, under optimal (foveal, full-attention) conditions, for the target set used in the experiment.

In the full-attention sessions, a fixation point was presented for 668 msec at the center of the display. It was then replaced by one of the four T-like target figures, which remained on the screen for a randomly selected duration before being replaced by the mask. The observer then indicated with a keypress which one of the four targets had appeared. The six possible target durations ranged from 16.7 to 100 milliseconds in 16.7-millisecond intervals.

Results and Discussion

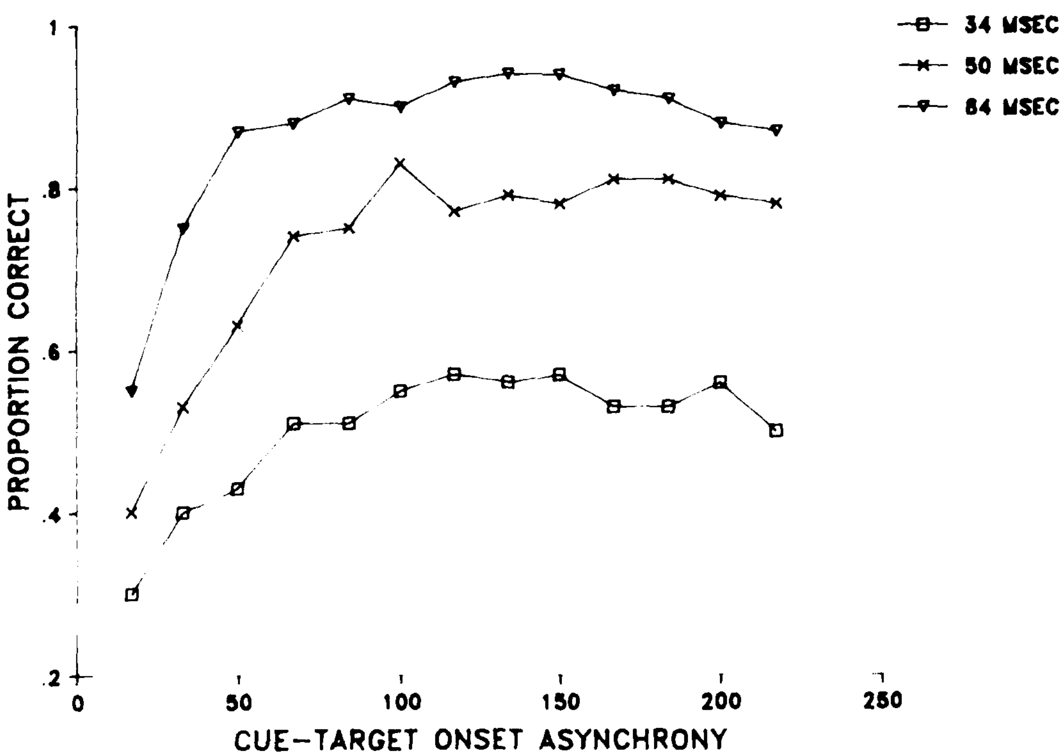

Figure 6. Proportion of Correct Discriminations as a Function of CTOA for Target Durations of 34, 50, and 84 msec, Experiment 3.

Figure 6 shows discrimination performance in the experimental sessions as a function of CTOA for all three target durations. Several facts are evident from this figure, in addition to the expected significant effect

of target duration on average performance ($x^2[2] = 677.2$, $p < .001$). First, for each target duration, there was a significant increase in performance between CTOAs of 17 and 34 msec (84-msec TD: $x^2[1] = 16.6$, $p < .001$; 50-msec TD: $x^2[1] = 9.8$, $p < .005$; 34-msec TD: $x^2[1] = 7.7$, $p < .01$). This is clear evidence against a long-latency model, since such a model would predict that the shorter the target duration, the longer the CTOA required to show an initial rise in performance. Moreover, the fast-rising parts of the curves were not parallel (50-34 msec: $x^2[3] = 35.1$; 84-50 msec: $x^2[3] = 21.5$; 84-34 msec: $x^2[3] = 27.5$; all $p < .001$). As target duration increased, the steeper the slope of the curve became, and the earlier the asymptote was reached.

Thus, all of the results suggested by the target-duration comparisons in Experiment 2 were observed in this experiment, including those that argue against a long-latency model. In particular, the significant performance improvement observed between CTOAs of 17 and 34 msec for a 34-msec target duration indicates that attention is beginning to affect performance within 68 msec of cue onset.

The results also indicate how long attention effects last. Curves for longer target durations asymptote at correspondingly shorter CTOAs; that is, all curves asymptote at about the same total time since cue onset. This implies that attention effects continue to build up during target presentation at about the same rate as they do during the cue-target interval. An estimate of the duration of this buildup can be obtained by plotting average performance as a function of CTOA plus target duration (Figure 7). The figure shows that attention effects cease 120-150 msec after cue onset.

Finally, the results suggest that attention moderates the relationship between target duration and discrimination performance. Figure 8 shows proportion correct as a function of target duration, with CTOA as a parameter. Only data from the first six CTOAs (the ones that account for virtually all of the observed attention effects) are shown. As CTOA increases, there is a systematic increase in the slope of the initial segment of the lines, the part that represents an increase in target duration from 34 to 50 msec. (The 84-msec target duration is not included in the slope because performance is at asymptote for CTOAs over 50 msec.) For example, the slope obtained with a CTOA of 100 msec (0.017) is nearly triple that observed with a CTOA of 17 msec (0.006). This effect was highly significant in the overall data ($x^2[5] = 67.1$, $p < .001$) and for each of the three observers (observer 1: $x^2[5] = 29.9$, $p < .001$; observer 2: $x^2[5] = 19.3$, $p < .005$; observer 3: $x^2[5] = 34.0$, $p < .001$). A possible interpretation is that focusing spatial attention on the target location increases the rate at which information is extracted from the target.

This interpretation is further supported by the observation that the slope increase is not simply a consequence of better asymptotic performance at longer CTOAs. Examination of the top three lines of Figure 8 shows that even though asymptotic performance is similar in all three, it is reached sooner for the lines representing longer CTOAs. Hence, if the

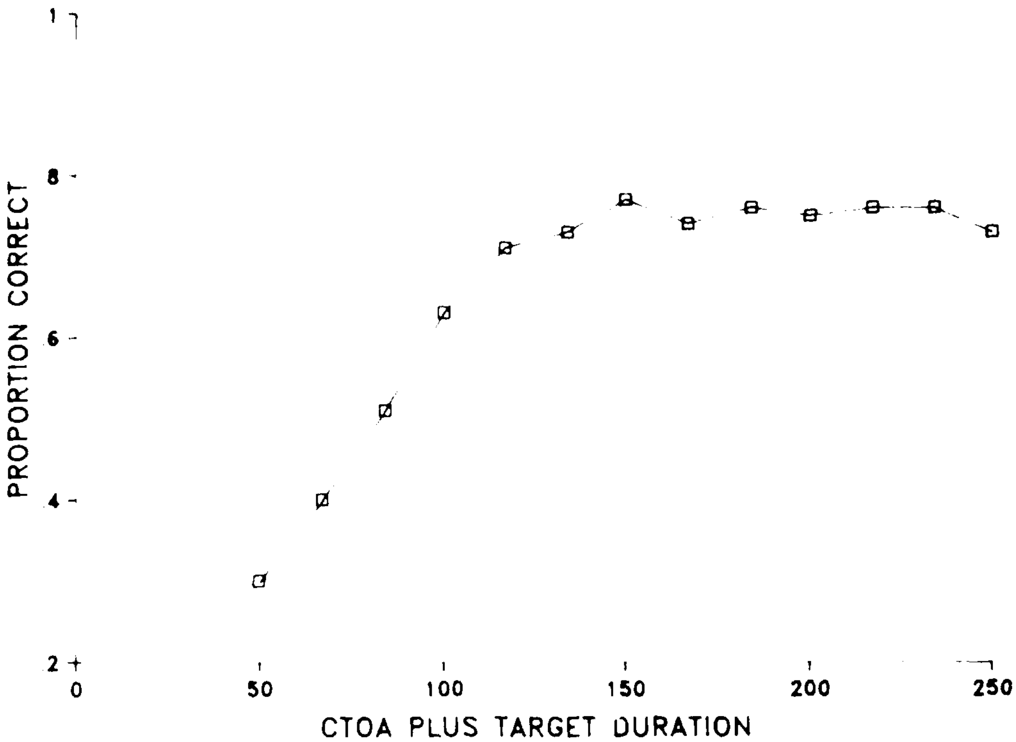

Figure 7. Proportion of Correct Discriminations as a Function of Total Time Available to Shift Attention (CTOA Plus Target Duration), Experiment 3. Points on the curve are averages over all three target durations (34, 50, and 84 msec), except for the first point, which necessarily contains only data from the 34-msec target duration, and the second point, which contains only data from the 34-msec and 50-msec target durations.

effect of increasing target duration is to allow more information to be extracted from the target, then the effect of attending internally to the target is to speed up this extraction process.

If this interpretation is correct, then the full-attention condition that was run before and after the experimental trials should show a target-duration effect that is at least as steep as that obtained for the 100-msec CTOA trials in Figure 8. Figure 9 shows performance in the three full-attention condition sessions. There is a large pre/post effect on the slope of these curves ($x^2[3] = 87.5$, p .001). Nevertheless, it is clear from the post-experiment data that a very steep target-duration effect is observed, just as it was in the long-CTOA data of Figure 8, since in both cases attention was focused on the target area when the target appeared.

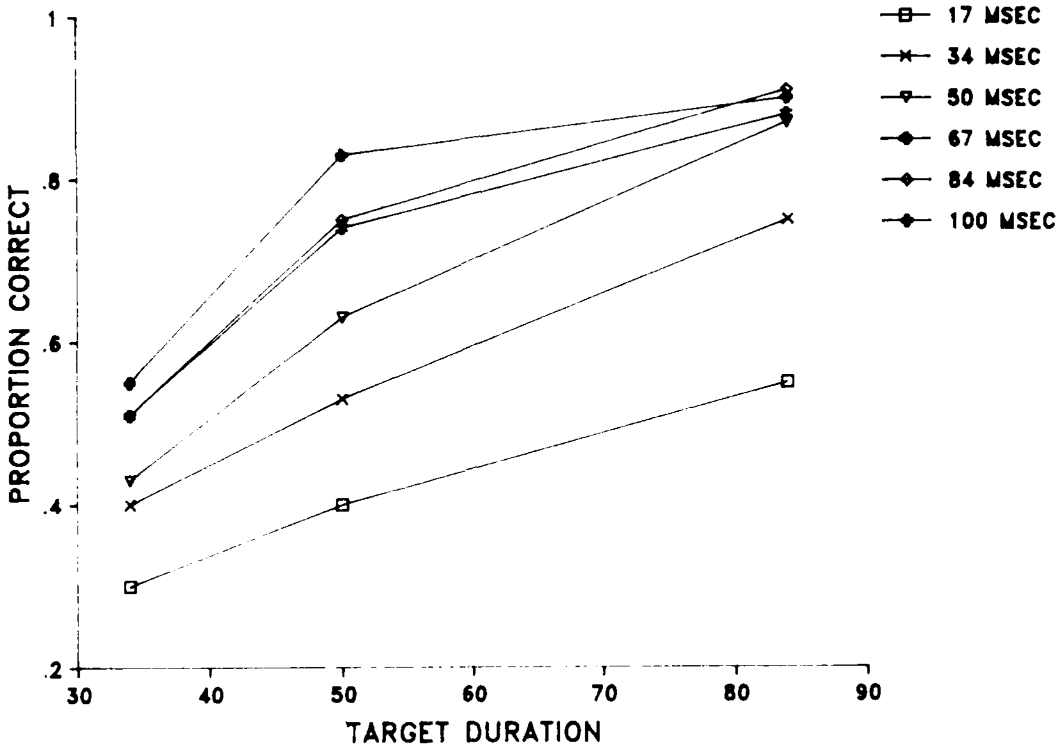

Figure 8. Proportion of Correct Discriminations as a Function of Target Duration, with CTOA as a Parameter. This is a replotting of the data from the fast-rising parts of the curves in Figure 6. It shows that the initial slope of the target-duration effect increases with CTOA.

To summarize, the results of Experiment 3 indicate that: (a) Effects of attention begin at the target location in less than 68 milliseconds, perhaps much less. (b) Attention effects continue until 120-150 msec after the presentation of the cue, regardless of target duration; they are not terminated by the presentation of the target. (c) Attention increases the rate at which information is extracted from the target.

In order to obtain more precise estimates of the latency and duration of attention effects, the results were formalized as a quantitative model. Let L denote the number of milliseconds after cue onset at which attention effects begin, and M denote the time at which they end; then, the time during which attention is having an effect on the information in the cued location is:

$$\text{Attention Duration (AD)} = \min(M, (TD + CTOA)) - L. \qquad (2)$$

If attention increases the rate of information extraction from the target, then performance should be a multiplicative function of attention duration and target duration; that is:

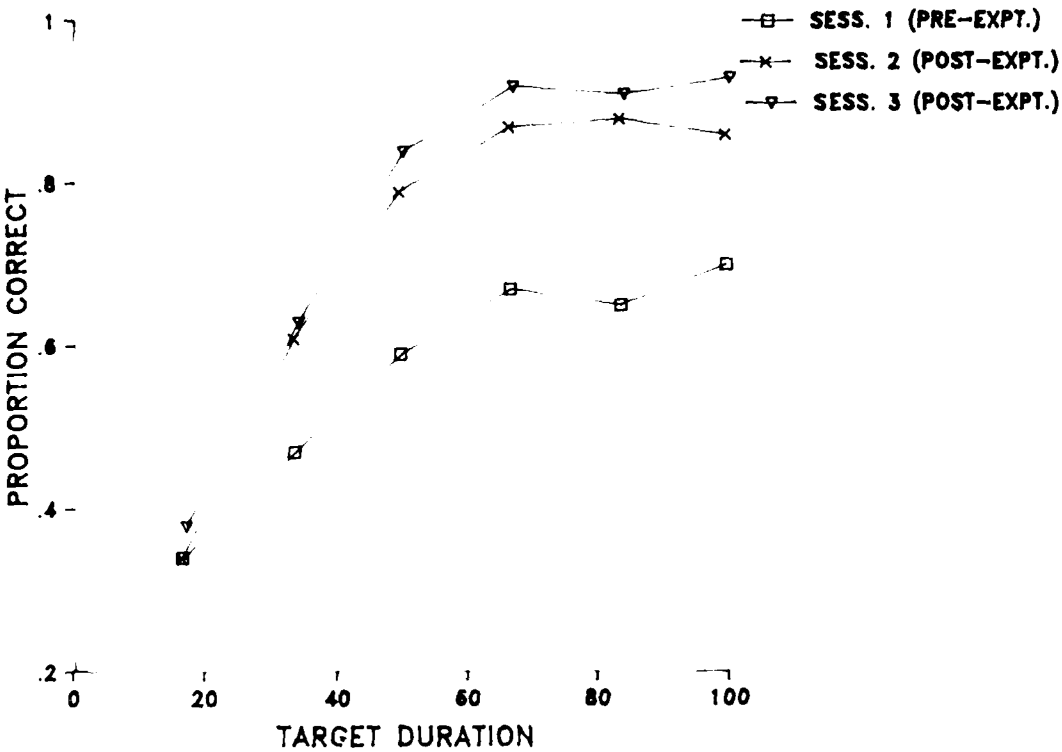

Figure 9. Proportion Correct as a Function of Target Duration in the Full-Attention Condition, Experiment 3.

$$\text{Proportion Correct} = AD * TD * B + C \qquad (3)$$

where B and C are slope and intercept constants.

This four-parameter model fits the data from the 34-msec and 50-msec target durations quite well. When the model was fit to the first eight points of the 34-msec and 50-msec data (to avoid including the down-drifting presumably caused by occasional eye movements), the resulting parameter values were L = 22, M = 122, b = .000119, and c = .18. Thus, the best model fit was obtained with an attention latency estimate of 22 msec. The model closely reproduces the systematic increase in the slope of the target-duration effect with increasing CTOAs (Figure 8) and the cessation of attention effects after about 120 milliseconds (Figure 7).

In order to account for the data from the 84-msec target duration condition, one change in the model was required. Data from the full-attention condition (Figure 9) indicated that discrimination performance asymptotes at a target duration of between 50 and 67 milliseconds. Therefore, the actual target duration of 84 msec was replaced in Equations 2 and 3 with a new parameter representing asymptotic target duration.

The resulting model was fit to the data for all three target durations. The values given above for the original four parameters were fixed; only the new asymptotic target-duration parameter was allowed to vary. The value of this parameter was thus estimated to be 62, which is within the range indicated by the data from the full-attention condition. Figure 10 shows the fit of this model to the data from all target durations. It is clear that the parameter values that fit the data from the shorter durations also fit the 84-msec data quite well, once the asymptote in target-duration effects is taken into account.

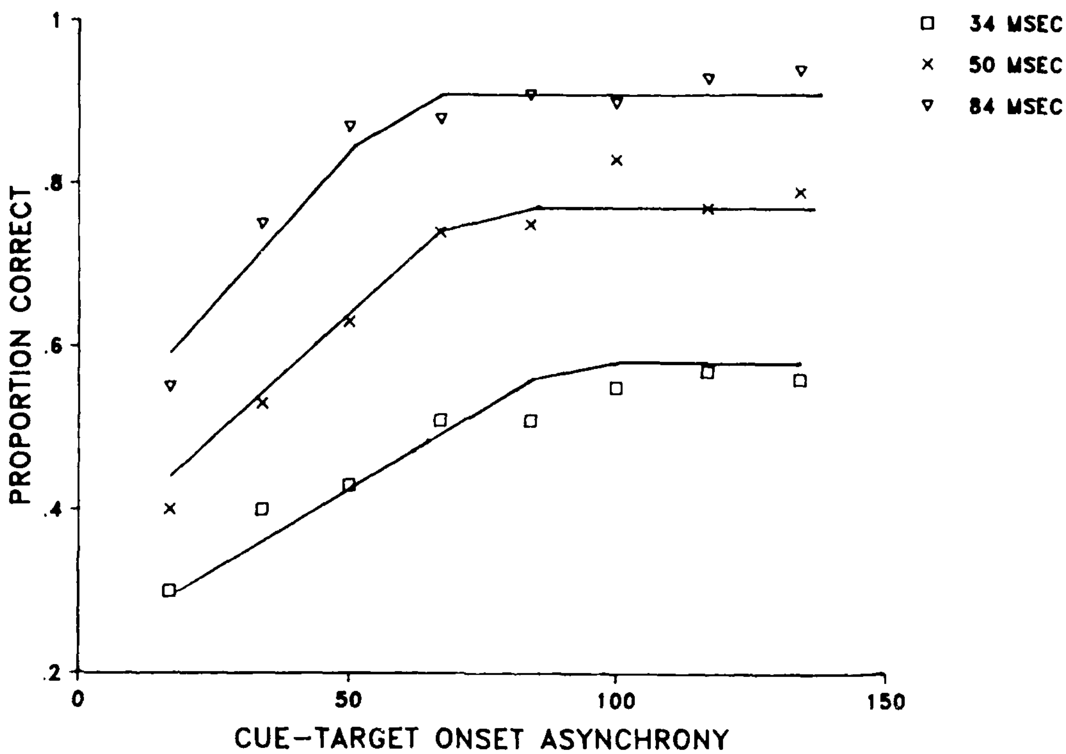

Figure 10. Comparison of Predicted and Actual Proportion of Correct Responses for Target Durations of 34, 50, and 84 msec, Experiment 3. Solid Lines are the predictions obtained via Equations 2 and 3 (see text).

V. GENERAL DISCUSSION

The purpose of these experiments was to determine how quickly shifts of internal visual attention can affect form perception. Previous research in which a brief change in luminance was used as a target had shown that when attention was cued by the onset of a stimulus in the target area, attention effects were evident much sooner after cue presentation than was the case when cues presented at fixation were used (Posner, 1980: Posner & Cohen, 1984; Remington 1980; Remington & Pierce, 1984).

Experiment 1 replicated this effect for a form discrimination task, and Experiment 2 showed that the difference in attentional latency between foveal and target-area cues could be largely eliminated with practice. This latter result argues against certain non-attentional explanations of the target-area cue effect (such as masking). Experiment 2 also uncovered several differences between the time course of attention effects for different target durations. These differences were observed again in Experiment 3, where it was also shown that (a) the latency of attention effects is less than 68 msec, (b) attention effects continue to build up during the presentation of the target but cease at 120-150 msec after the cue, and (c) attention increases the rate at which target presentation time improves discrimination performance. A quantitative model incorporating these findings was successful in accounting for the observed effects of CTOA and target duration.

Attention Latency and Perception

These results have important implications for the general question posed in the introduction; namely, are internal shifts of attentional focus fast enough to be involved in constructing the visual percept?

Under optimal conditions in these experiments, the latency of attention effects was estimated to be under 50 msec, even considering the possibility that attention could shift during the presentation of the target. Studies of attention effects on detection of luminance increments using reaction time to target-area cues as the dependent variable have also reported the existence of attention effects within 50 milliseconds of cue onset (Posner, 1980). Since this time presumably includes the time to process the cue to shift attention, and perhaps other operations as well, the actual time required for the focus of attention to change is clearly fast enough to allow a serial process to select many different processing locations during a single fixation.

However, there remain at least two possible objections to the idea that rapid internal attention shifts underlie some aspects of perceptual processing. One is that even if a new attended location can be selected in a few milliseconds, perceptual processing at the new location will surely take much more time. If such processing requires attention, then fewer shifts of processing focus will be possible within a typical fixation. In the present experiments, for example, attention continued to affect performance for at least 120 milliseconds. Thus, for the present task, at most only two or three discriminations requiring full attention could be performed during a fixation. Moreover, it might be possible to lengthen the time for which attention will affect processing (M-L) by increasing the amount of information that has to be extracted from the target.

The operations for which Treisman and Gelade (1980) and Ullman (1984) suggested a serial attention mechanism--operations such as feature conjunction or boundary tracing--may not require anything like a full accumulation of attention effects. Moreover, one can easily imagine a system in which computations are started in serial fashion at various index points, but the selection of each new index point does not depend on

the completion of the computation started at the preceding point. In such a system, the important parameter would indeed be the latency of the indexing operation.

A second possible objection rests solely on observer introspection. In experiments such as those reported here, the observer has the distinct impression that at least small amounts of time and effort are being used in focusing attention on the cued region. Yet, elsewhere, the perception of complex scenes--which must result from many, perhaps dozens of successive attention shifts--seems effortless. Of course there are many possible answers to an objection like this, but one such answer is that the feeling of conscious effort is tied to the accumulation of attention effects. It may be that merely changing the locus of processing is not effortful; and if perceptual operations such as boundary tracing or feature conjunction are then performed, one will not be conscious of them. However, if one attempts to enhance vision at a location by focusing attention on it, then this buildup of attention effects will be found to be effortful.

Components of Attention

Implicit in the foregoing discussion is a strong separation between (a) the changing of the locus of visual processing, whether it be for the purpose of attending to a location or performing some other computation, and (b) the enhancement of vision when attention has been focused on a location.

This distinction has been discussed at some length by Posner, Walker, Friedrich, and Rafal (1984). They proposed that there are actually three components to a change in the focus of internal attention: First, attention must be disengaged from its current focus; then the focus of attention is moved across visual space; and, finally, the effects of attention build up at the target location. These operations are called, respectively, the "disengage," "move," and "engage" operations. Posner et al., argued that, based on performance experiments using individuals with specific brain damage, there is good evidence that these operations are localized in different parts of the brain, and each operation takes a measurable amount of time.

The model derived from the results of the present experiments allows one to estimate separately the temporal characteristics of processes responsible for shifting attention to the target location (perhaps the disengage or move operations) and processes that result in improved performance once attention has arrived there (the engage operation).

In determining how quickly attention effects begin at a new location, it seemed unnecessary to adopt a position concerning the nature of the attention mechanism. None of the present findings appears to contradict either a moving spotlight (Shulman et al., 1979), zoom lens (Eriksen & Yeh, 1985), or gate opening (Reeves & Sperling, in press) view of attention.

The present results do, however, shed some light on what happens once attention reaches a location. Attention seems to increase the rate at

which information from the target location accumulates, as reflected in an increased proportion of correct discriminations. This rate increase is not simply a reflection of better overall performance with increasing attention. The data show that when sufficient time was allowed for shifting attention, most of the useful target information was extracted between 34 and 50 msec, and performance increased little between 50 and 84 msec. However, when less shifting time was available, information was still accumulating at the longer target durations.

Conclusion

These experiments give evidence that internal attention shifts are fast enough to help construct the visual percept. Since attention can apparently shift within a few milliseconds, it could possibly be used in conjoining features of objects, localizing objects relative to one another, and perhaps other fundamental aspects of perception.

The fact that it took roughly 120 msec for the effects of attention to asymptote in the present experiments, and even longer in some other experiments, does not necessarily mean that 120 msec is the time required to change the location being attended. Rather, it is likely that most of this time represents an accumulation of the attentional effects necessary to discriminate very similar and briefly presented peripheral targets. The easier the discrimination that is required, the faster a given level of performance could be reached.

In a real scene composed of relatively distinct objects, the amount of attention required to conjoin the color and form of large objects might be minimal. Thus, many rapid shifts could be executed in the short time that it takes to perceive the main elements of such a scene.

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